Accelerated Development of Innovative Clean Energy Systems:
Post-K Project Priority Issue 6

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https://postk6.t.u-tokyo.ac.jp/en/
Priority Issue 6
Accelerated Development of Innovative Clean Energy Systems
(Leader : S. Yoshimura, UTokyo) (2014.12-2020.3)

Sub Issue A : Energy Conversion Systems Accompanied by High-pressure Combustion and Gasification
(Leader : S. Yoshimura)

Sub Issue B : Advancement of Fuel Cell Design Process
(Leader : N. Shikazono, UTokyo)

Sub Issue C : High-efficiency Wind Power Generation System
(Large Scale Offshore Wind Farm)
(Leader : A. Iida, Toyohashi University of Technology)

Sub Issue D : Core Design of Fusion Reactor
(Leader : Y. Idomura, Japan Atomic Energy Agency)
33. Development of Exascale Fusion Plasma Turbulence Simulations for Post-K
(Y. Idomura, T. Ina, K. Obrejan, Y. Asahi, S. Matsuoka, T. Imamura)

34. Communication Avoiding Multigrid Preconditioned Conjugate Gradient Method for Extreme Scale Multiphase CFD Simulations
(S. Yamada, N. Onodera, T. Ina, S. Yamashita, Y. Idomura, T. Imamura)

36. Extended Kinetic-Magnetohydrodynamic Hybrid Simulations of Magnetically Confined Laboratory Plasmas
(Y. Todo, M. Sato, H. Wang, R. Seki)

37. Communication Reduced Multi-Time-Step Algorithm for the AMR-based Lattice Boltzmann Method on GPU-rich Supercomputers
(N. Onodera, Y. Idomura, Y. Ali, T. Shimokawabe)
67. LES Modeling and Simulation of Coal Gasification on an O$_2$-CO$_2$ Blown Coal Gasifier
   (H. Watanabe, R. Kurose, K. Tanno)

68. Large-eddy Simulation of a Supercritical CO$_2$ Combustion Field in a Realistic Combustor
   (P. Jain, Y. Iwai, Y. Kobayashi, M. Itoh, T. Nishiie, R. Kurose)

70. Large-eddy Simulation of Combustion Instability of Spray Combustion: Effect of Time Fluctuation of Liquid Fuel Mass Flow Rate
   (J. Nagao, A. Pillai, R. Awane, R. Kurose)

73. Fully Coupled Simulation of Coal Gasification System Using LES based Solver for Combustion and Thermal Conduction Solver in Vessel
   (T. Yamada, N. Mitsume, H. Watanabe, R. Kurose, H. Uchida, S. Yoshimura)
Sub Issue A

**Multiscale and Multiphysics Simulations of Coal Gasification Plant**
Including Reaction (Combustion, Gasification, Particle Tracing, Slug Melting) – Thermal Conduction – Cooling – Deformation
**Overview of Coal Gasification Plant**

**REVOCAP_Coupler**: Two-way coupling simulation of thermo-fluid–structure and cooling phenomena

**ADVENTURE_Thermal (FEM)**: Thermal Conduction in vessel as well as cooling by water in cooling pipes

**Particulated coal**

**Cooling systems by water in pipes**

**Slug goes downwards**

**Assessment of heat transfer at coupling interface**

**Attachment and solution of coal ash**

**Assessment of elevated-temperature structural integrity**

**Assessment of complex thermo-fluid combustion dynamics**

**FFR-Comb (FVM)**: Combustion, gasification and particle tracing models

**Ash solution (solid-gas-liquid three-phase model)**

**ADVENTURE_Solid (FEM)**: Nonlinear material behavior and damage assessment under elevated-temperature and high-pressure environments
## Relations among Applications

<table>
<thead>
<tr>
<th>Application</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>FFR-Comb (FVM)</td>
<td>Combustion Flow (Gas-Liquid-Particles)</td>
</tr>
<tr>
<td>REVOCAP_Coupler #1</td>
<td>Two-way Coupling on K-computer</td>
</tr>
<tr>
<td>ADVENTURE_Thermal (FEM)</td>
<td>Thermal Conduction in Vessel and Cooling</td>
</tr>
<tr>
<td>EVOCAP_Coupler #2</td>
<td>Off-line One-way Coupling</td>
</tr>
<tr>
<td>ADVENTURE_Solid (FEM)</td>
<td>Nonlinear Thermal Fatigue, Structural Integrity</td>
</tr>
</tbody>
</table>

Heat Flux ($Q$) ↔ Wall Temperature ($T_w$) ↔ FFR-Comb (FVM) with Cooling by Pipes

Temperature ($T$) ↔ ADVENTURE_Solid (FEM)

Online Two-way Coupling ↔ REVOCAP_Coupler ↔ Off-line One-way Coupling
CAD Model | 1D Model of Cooling Pipes

<table>
<thead>
<tr>
<th></th>
<th>Fluid model</th>
<th>Solid model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nodes</td>
<td>23,883,517</td>
<td>25,510,852</td>
</tr>
<tr>
<td>Elements</td>
<td>118,803,415</td>
<td>155,999,061</td>
</tr>
<tr>
<td>Kinds of Elements</td>
<td>Tet, Prizm, Pyramid, Hex</td>
<td>Tet</td>
</tr>
<tr>
<td>Coupling Nodes</td>
<td>634,678</td>
<td>243,024</td>
</tr>
</tbody>
</table>
### Calculation Conditions of Combustion Flow Region for FFR-Comb

<table>
<thead>
<tr>
<th></th>
<th>Flow model</th>
<th>Turbulence model</th>
<th>Time integration</th>
<th>FD Scheme for convection term</th>
<th>Time increment</th>
<th>Char reaction</th>
<th>Gas reaction</th>
<th>Initial condition</th>
<th>Temperature BC at Wall</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Zero Mach Approximation</td>
<td>DLES</td>
<td>Euler Implicit</td>
<td>Eq. of Motion: 2(^{nd}) Order Central Difference (95%)</td>
<td>5.0 × 10(^{-6}) s</td>
<td>C + 0.5O2 → CO</td>
<td>CH4 + 0.5O2 → CO + 2H2</td>
<td>Initial pressure: 2 × 10(^6) Pa</td>
<td>Transfer condition, Tw=308K, htc=10.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Eq. of Energy: 2(^{nd}) Order Upwind</td>
<td></td>
<td>C + CO2 → 2CO</td>
<td>H2 + 0.5O2 → H2O</td>
<td>Initial temperature: 1273K</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>C + H2O → CO + H2</td>
<td>CO + 0.5O2 + H2O → CO2 + H2O</td>
<td>Initial mass density: 5.06kg/m(^3)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>CH4 + H2O → CO + 3H2</td>
<td>Initial chemical components: N2(57.26%) + CO2(18.69%) + CO(16.82%) + C(0.0053%) + ASH(0.0056%)</td>
<td></td>
</tr>
</tbody>
</table>

**CPU Time per Step:** 3 sec when using 9216 CPU (1152 nodes)
Coupling between 3D Thermal Conduction in Vessel and 1D Convection & Diffusion in Cooling Pipes

3D thermal conduction
- finite element method
- implicit time integration
- large-scale analysis

1D cooling pipe model
- local discontinuous Galerkin (LDG) method
- explicit time integration

Heat flux on pipe surface
↓
Source term of 1D analysis

Partitioned coupling scheme

Heat flux given by heat transfer B.C.
Multiscale and Multiphysics Simulations of CRIEPI’s Coal Gasification Plant Including Reaction (Combustion, Gasification, Particle Tracing, Slug Melting) – Thermal Conduction – Cooling – Deformation

Combustor (Combustion, Gasification, Particles, Slug)

Vessel (Thermal Conduction, Deformation)

Cooling Pipes (Convection-Diffusion)

Fluid Model Coupling

FFR-Comb (FVM, LES) (Parallel Coupling)
1.19M elements
Δt=10^{-6}

REVOCAP_Coupler
0.63M fluid nodes
0.24 Structure nodes

ADVENTURE (FEM)
1.56M elements
Δt=10^{-2}

Two-way Coupling

Combustion Temperature

CO distribution

Vessel Temperature

Combustion Slug Melting
Parallel Two-way Coupling of FFR-Comb ⇔ REVOCAP_Coupler ⇔ ADVENTURE on the K computer

Pre, Post Processors

Parallel Coupler

Exchange of physical Values

Utilization of Multiple Independent Parallel Solvers

Actual, Large-scale, Complex shaped

General-purpose

High Parallel Efficiency

Parallel Flow Solver

Parallel Solid Solver

MPI Communication

Socket communication → MPI

(socket version)

Socket communication → MPI

(MPI version)

<table>
<thead>
<tr>
<th>Analysis Case</th>
<th>Solid Subdomains</th>
<th>Time Steps</th>
<th>CPU Time (hrs)</th>
<th>Time for Pre-process※1 (s)</th>
<th>CPU Time for Flow Analysis (s/step)</th>
<th>CPU Time for Thermal Conduction Analysis (s/step)</th>
<th>CPU Time for Others (s/step)</th>
<th>Time for Output (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>128</td>
<td>5000</td>
<td>19</td>
<td>1501.5</td>
<td>2.60</td>
<td>8.97</td>
<td>0.11</td>
<td>107.0</td>
</tr>
<tr>
<td>2</td>
<td>2048</td>
<td>15000</td>
<td>25 ※2</td>
<td>2856.8</td>
<td>2.68</td>
<td>0.66</td>
<td>0.13</td>
<td>219.2</td>
</tr>
</tbody>
</table>

Subdomains in Flow Region: 9216 (9216 cores (1152 nodes))
Sub Issue C

Multiscale and Multiphysics Simulations of Offshore Wind Farm to Evaluate Power Generation Efficiency and Accumulated Fatigue Damages of Blades
### Wind Turbine of NREL 5MW

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotor Operation</td>
<td>Upwind</td>
</tr>
<tr>
<td>Number of Blades</td>
<td>3</td>
</tr>
<tr>
<td>Rotor Diameter</td>
<td>126 m</td>
</tr>
<tr>
<td>Hub Diameter</td>
<td>3 m</td>
</tr>
<tr>
<td>Hub Height</td>
<td>90 m</td>
</tr>
<tr>
<td>Tip Speed</td>
<td>80 m/s</td>
</tr>
<tr>
<td>Tip Speed Ratio In Benchmark Test</td>
<td>7.0</td>
</tr>
</tbody>
</table>

**Various Nonlinear Fluid Dynamics Phenomena**

- Meandering of Wake
- Interaction among Turbines via Wakes
- Effect of Peeling Flow from Nacelle and Tower onto Wake
- Effect of Wake onto Power Generation Efficiency and Structural Reliability

➡ Key Issues in Site Selection, Optimum Design and Arrangement, Operation Cost Reduction

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**Wake Meandering**

Turbine AV04 experiences meandering single wake from AV10.

- Flow
- Approx. 13D (D=126m)

Lidar Scanning (PPI: Plan Peripheral Indicator) at Alpha Ventus Offshore Wind Farm

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**Wake Interaction**

Actuator Line Modeling of Wind Turbine Wakes by using RIAM-COMPACT
Multiscale and Multiphysics Simulations of Offshore Wind Farm for Evaluation of Power Generation Efficiency and Fatigue Damages of Blades

**RIAM-COMPACT for HPC**
- Simultaneous Analyses for 16(24) Wind Directions by Parallel LES Analyses
- Engineering Wake Model
- Hundreds M to B Elements

**FFB**: LES-based Simulation of Tandem-placed Large-scale Wind Turbines
- Over 10 B Elements
- Wall Model

**REVOCAP_Coupler**
- One-way Coupling
- Fluid Loading acting to Blades

**ADVENTURE_Solid**: Analysis of Accumulated Fatigue Damage of Blade consisting of Orthogonal Anisotropic Laminated Solid Elements

- Two-way Coupling
- Blade’s Deformation (→LES Analysis)
Off-line One-way Coupling Analyses of NREL5MW Blade

CFD Results (FFB on K computer) → (Abstraction)

Time Variations of Fluid Loading Distributions on the Surface of Blade → REVOCAP_Coupler
Mapping of the above Fluid Loading onto the Surface of Blade Mesh

CFD Analysis Model (Tandem placement)

ADVENTURE_Solid
Dynamic Stress Analyses of Blade Structure → Analyses of Accumulated Fatigue Damage

Instantaneous Flow Field in the direction of main stream
Example of Evaluation of Accumulated Fatigue Damage Evaluation

- Time Variation and Spatial Distribution of Fluid Loading by FFB on K
- Atmospheric Boundary Layer, Turbulence, Wake
- Time Variation and Spatial Distribution of Stress in Blade by ADVENTURE_Solid
- Rainflow Counting + Goodman Diagram + S-N Curve + Yeary Wind History

Cumulative Fatigue Damage in Blade

- Leading Edge (LE)
- LE Panel
- Spar Cap
- Shear Web
- TE Panel
- TE Reinforcement
- Trailing Edge (TE)

Enlargement

Relatively Larger Damage of Fatigue

1.0 m span

30.0 m span

7.1 m span

60.0 m span

25 Material Groups
Hex Laminated Solid Element
Total Elements: 289,202
Total DOFs: 484,461
Thank you for your attention!

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